

## Stealth gluons at hadron colliders

R. Barceló,<sup>\*</sup> A. Carmona,<sup>†</sup> M. Masip,<sup>‡</sup> and J. Santiago<sup>§</sup>

*CAFPE and Depto. de Física Teórica y del Cosmos,*

*Universidad de Granada, 18071 Granada, Spain*

### Abstract

We find that a heavy gluon  $G$  of mass 800–900 GeV with small, mostly axial-vector couplings to the light quarks and relatively large vector and axial-vector couplings to the top quark can explain the  $t\bar{t}$  forward-backward asymmetry observed at the Tevatron with no conflict with other top-quark or dijet data. The key ingredient is a complete treatment of energy-dependent width effects and a new decay mode  $G \rightarrow qQ$ , where  $q$  is a standard quark and  $Q$  a vector-like quark of mass 400–600 GeV. We show that this new decay channel makes the heavy gluon *invisible* in the  $t\bar{t}$  mass invariant distribution and discuss its implications at the Tevatron and the LHC.

---

<sup>\*</sup>Electronic address: rbarcelo@ugr.es

<sup>†</sup>Electronic address: adrian@ugr.es

<sup>‡</sup>Electronic address: masip@ugr.es

<sup>§</sup>Electronic address: jsantiago@ugr.es

## I. INTRODUCTION

The Fermilab Tevatron is probing quark interactions up to energies  $\sqrt{s} \lesssim 800$  GeV. Its most significant discovery has been the top quark, with a mass around 172 GeV. This quark could turn out to be more than *just* the building block completing the third family of the standard model (SM). Since masses are not gauge invariant and it is the heaviest fermion, one expects that the top-quark sector holds the key to understand the mechanism of electroweak (EW) symmetry breaking. In particular, new particles (a scalar partner, a vector-like T quark) or a different (composite) nature have been proposed to explain the stability of the EW scale under top-quark radiative corrections.

In fact, CDF and D0 measurements imply an intriguing deviation with respect to the SM prediction in the  $t\bar{t}$  forward-backward asymmetry  $A^{t\bar{t}}$  [1]. We will take as reference value the one recently reported by the CDF collaboration,

$$A^{t\bar{t}} \approx \begin{cases} -0.116 \pm 0.153, & m_{t\bar{t}} < 450 \text{ GeV}; \\ 0.475 \pm 0.114, & m_{t\bar{t}} > 450 \text{ GeV}, \end{cases} \quad (1)$$

which refers to the asymmetry measured in the  $t\bar{t}$  center of mass frame. The SM prediction,  $0.040 \pm 0.006$  and  $0.088 \pm 0.013$  for the low and the high-energy regions, respectively, gives a three-sigma deviation at large values of  $m_{t\bar{t}}$  [1]. If caused by new physics, this unexpected result would be an order-one departure from the standard quark physics at 450–800 GeV, and similar anomalies could be expected in other observables at the Tevatron and the early LHC. However, the asymmetry has not been *supported* by current data on the total  $t\bar{t}$  cross section or the invariant-mass distributions of top-quark pairs and dijets. As a consequence, possible new particles proposed to explain it are typically pushed above 1–2 TeV, out of reach both from Tevatron energies and from the current LHC luminosity. Such high values, in turn, become ineffective to produce the large asymmetry or should be apparent with a slightly increased LHC luminosity, as general effective Lagrangian studies [2] indicate.

In this letter we show that a heavy gluon with mass 800–900 GeV can still explain the observed asymmetry with no conflict with current data. The mechanism that could hide the particle responsible for the asymmetry relies on a very large width caused by new decay channels opening at  $\sqrt{s} \lesssim 600$  GeV. This requires a careful treatment of the energy-dependent width of the heavy particle. The scenario predicts a predominantly right-handed polarization for the excess of forward top quarks and at least an extra 400–600 GeV new

quark. Another interesting test of the model is the value of the  $t\bar{t}$  charge asymmetry  $A_C$  at the LHC [3], since the relatively low mass of the gluon resonance implies a change in the sign at  $m_{t\bar{t}} \approx M_G$ . Our framework is natural in holographic Higgsless models [4], in which longitudinal  $W, Z$  scattering is unitarized by vector excitations of mass below 1 TeV [5]. In that case our results would imply strongly coupled physics right above the EW scale and no Higgs at the LHC.

## II. THE MODEL

The framework is defined by a massive gluon  $G$  with large couplings to the right-handed top quark, and small-close to axial ( $g_L^q \approx -g_R^q$ ) couplings to the light quarks:

$$\begin{aligned} g_R^q &= -(0.2-0.3)g, & g_L^q &= +(0.2-0.3)g, \\ g_R^t &= +(4-6)g, & g_L^t &\approx 0g. \end{aligned} \tag{2}$$

Couplings in this range are naturally obtained in holographic models after imposing consistency with precision EW bounds. In those models  $g_R^t$  *must* be large because the top lives in the brane that breaks the EW symmetry, together with all the massive excitations. The opposite sign of  $g_R^q$  and  $g_L^q$  and the small value of these couplings are required to reproduce the standard coupling with the EW gauge bosons. In turn, the sign difference optimizes the appearance of a FB asymmetry, whereas the size prevents an excess of dijet events mediated by the massive gluon. The first feature also implies that at  $\sqrt{\hat{s}} = m_{t\bar{t}} \ll M_G$  the contributions to  $d\sigma/dm_{t\bar{t}}$  from light quarks of different chirality tend to cancel each other [4].

We take a gluon mass  $M_G = 800-900$  GeV, as required in Higgsless models and hinted by Tevatron data on  $A^{t\bar{t}}$ . Finally, the *new* ingredient of the set up is the presence of a massive quark excitation  $Q$  that opens a new decay channel for the massive gluon or a new gluon-mediated process at  $\sqrt{\hat{s}} \approx 600$  GeV:

$$q\bar{q} \rightarrow G \rightarrow Q\bar{q}, \tag{3}$$

If  $Q$  is an excitation  $T$  of the  $t$  quark, it should have a relatively low mass,  $m_T = 400-500$  GeV. However, if it decays predominantly into  $Wb$  it will produce the same  $WWb\bar{b}$  signal as  $t\bar{t}$  production and could give an unobserved effect at  $m_{t\bar{t}} \geq 600$  GeV. The same contribution

could be obtained from an excitation  $B$  of the  $b$  quark that decays significantly into  $Wt$  (see discussion below). Due to the different kinematics, a definite statement about the visibility of these final states in current data requires a detailed analysis that is beyond the scope of this letter and will be presented elsewhere. Therefore, we consider the *cleanest* possibility, namely the presence of one or several heavy quarks  $Q$  that are excitations of the light quarks ( $Q = U, D, S, C$ ) and decay into  $W/Z$  plus jet. The mass of these quarks should be below 600 GeV. To simplify our analysis we will assume a single particle  $Q = U$  and all other quark excitations above the production threshold in  $G$  decays ( $m_Q + m_q > M_G$ ). We would like to emphasize that the results for other choices of  $Q$  in terms of pure  $t\bar{t}$  production are very similar, although their collider implications can vary from one case to the other.

### III. ROLE OF THE $Q$ QUARK

Let us start describing the situation in absence of the extra  $Q$  quark. It has been shown [4] that the gluon mass and the couplings in Eq. (2) are able to produce a large FB asymmetry (within 1.5 sigmas of the measured value at  $m_{t\bar{t}} \geq 450$  GeV) consistently with bounds from dijet searches. However, there seems to be some tension with the data on  $d\sigma/dm_{t\bar{t}}$  at  $m_{t\bar{t}} \geq 600$  GeV, near the gluon mass. This tension is weak at the  $5.3 \text{ fb}^{-1}$  Tevatron, but becomes more clear at the  $0.2 \text{ fb}^{-1}$  LHC, where the peak of the gluon resonance should be visible. One could hope that an increase in the coupling  $g_R^t$  will increase the gluon width and smear out the peak. However, the fit does not improve because the total cross section also goes up with  $g_R^t$  and, most notably, the asymmetry  $A^{t\bar{t}}$  seems to decrease.<sup>1</sup> This last effect can be understood because the gluon width appears in the denominator of the  $t\bar{t}$  production amplitude, and larger values (similar to its mass) will suppress the effects of the massive gluon and thus the predicted asymmetry.

However, as we increase the gluon width the fixed-width approximation, standard in current MonteCarlo generators, becomes worse. Its energy dependence (see for example [7, 8]) can be easily computed from the imaginary part of the gluon 2-point function. We

---

<sup>1</sup> This is the main argument behind recent claims in the literature that heavier axigluons are favoured over lighter ones [6, 7].

get

$$\Gamma_G^{t\bar{t}}(\hat{s}) = \frac{g^2}{24\pi M_G} \left(1 - \frac{4m_t^2}{\hat{s}}\right)^{\frac{1}{2}} \left[ \left(1 - \frac{4m_t^2}{\hat{s}}\right) g_A^{t2} + \left(1 + \frac{2m_t^2}{\hat{s}}\right) g_V^{t2} \right] \theta(\hat{s} - 4m_t^2). \quad (4)$$

In our simulations we have used MADGRAPH/MADEVENT v4 [9], with PYTHIA [10] for hadronization/showering effects and PGS4 [11] for detector simulation. We have modified the matrix element in the fortran code generated by MADGRAPH to include the energy dependence of the width. This correction tends to increase the effects of the new physics at low energies. For example, for  $g_R^t = 6g$  the asymmetry at  $m_{t\bar{t}} > 450$  goes from 0.17 in a simulation with a constant width to 0.20 using the width given in (4). However, we have found that the effect in the invariant mass distribution is small, and the change in slope at  $m_{t\bar{t}} \geq 600$  GeV would still conflict with the data.

The effect of the extra  $Q$  quark is then crucial, by opening the new decay channel  $G \rightarrow q\bar{Q}, \bar{q}Q$  at  $\sqrt{\hat{s}} \approx 600$  GeV. Below those energies the process is irrelevant (it does not contribute to the imaginary part of the propagator), so the FB asymmetry at 450–600 GeV is unchanged. At  $m_{t\bar{t}} \geq 600$  GeV, in contrast, this decay channel will *dissolve* the peak without increasing the number of  $t\bar{t}$  pairs produced. Its energy-dependent partial width is

$$\begin{aligned} \Gamma_G^{q\bar{Q}, Q\bar{q}}(\hat{s}) = & \frac{g^2}{12\pi M_G} \left(1 - \frac{(m_q + m_Q)^2}{\hat{s}}\right)^{\frac{1}{2}} \left(1 - \frac{(m_q - m_Q)^2}{\hat{s}}\right)^{\frac{1}{2}} \times \\ & \left[ \left(1 - \frac{m_q^2 + m_Q^2 + 6m_q m_Q}{2\hat{s}} - \frac{(m_Q^2 - m_q^2)^2}{2\hat{s}^2}\right) g_A^{Q2} + \right. \\ & \left. \left(1 - \frac{m_q^2 + m_Q^2 - 6m_q m_Q}{2\hat{s}} - \frac{(m_Q^2 - m_q^2)^2}{2\hat{s}^2}\right) g_V^{Q2} \right] \theta(\hat{s} - (m_q + m_Q)^2). \quad (5) \end{aligned}$$

We take as a benchmark model the following values of the parameters

$$\begin{aligned} M_G &= 850 \text{ GeV}, \quad M_U = 500 \text{ GeV}, \\ g_L^q &= -g_R^q = -g_R^b = 0.3g, \\ g_L^b &= g_L^t = 0, \quad g_R^t = 4g, \\ g_R^{uU} &= 7.6g, \quad \text{all other couplings} = 0 \end{aligned} \quad (6)$$

We have chosen the coupling of the heavy gluon to  $uU$  in such a way that the total width at the gluon mass is  $\Gamma_G = 0.7 M_G$ . We plot in Fig. 1 the event distribution for this model with and without the  $uU$  channel included (solid and dashes, respectively) together with the SM prediction (dotted line). It is clear from the figure that without the new channel

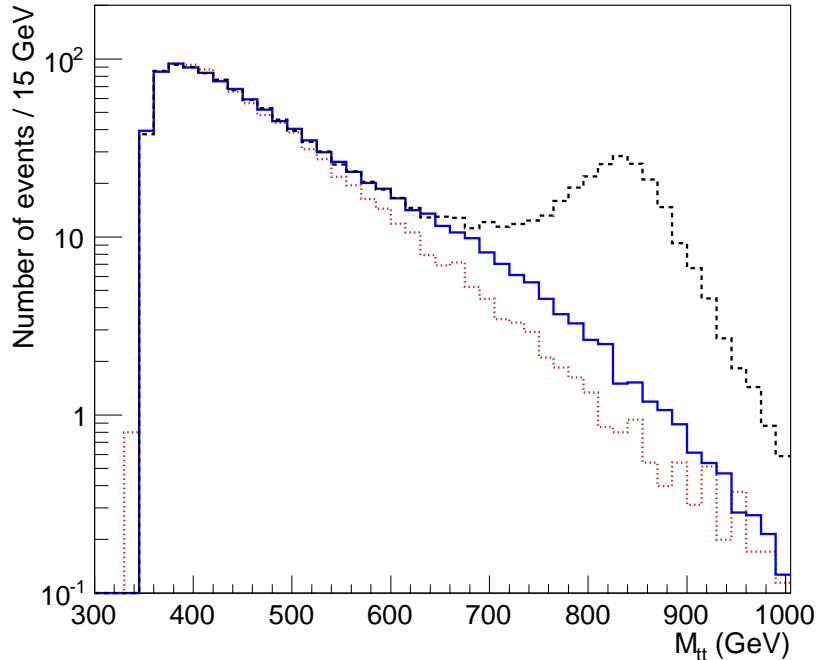


FIG. 1: Prediction for the  $m_{t\bar{t}}$  distribution at the Tevatron with a luminosity of  $5.3 \text{ fb}^{-1}$  for the SM (dotted) and for the model defined in Eq. (6) with (solid) and without (dashes) the new channel  $G \rightarrow U\bar{u}$ .

the peak is clearly visible. Once it is included the large width makes the gluon completely invisible. Including the SM contribution, the FB asymmetry in the large  $m_{t\bar{t}}$  region goes from  $A^{t\bar{t}} = 0.30$  with no extra  $U$  quark to  $A^{t\bar{t}} = 0.33$  in this model, just  $1.2 \sigma$  away from the measured value.

It is then clear that our *stealth*-gluon model can reproduce the Tevatron data on the forward-backward asymmetry and  $m_{t\bar{t}}$  distribution. Analogous observables could also test the model at the LHC [12]. We show in Fig. 2 the expected  $m_{t\bar{t}}$  distribution there for  $1 \text{ fb}^{-1}$  of integrated luminosity. We have followed the analysis in the first reference in [12] and taken the 4 jet, 2  $b$  tags in the muon channel as an example. It is clear from the figure that, given the uncertainties in the  $t\bar{t}$  normalization, this gluon is also invisible at the LHC.

#### IV. OTHER IMPLICATIONS AT HADRON COLLIDERS

As we have already mentioned, the small couplings  $(0.2\text{--}0.3)g$  of the massive gluon to the light quarks implies an acceptable contribution to dijet data. However, a 400–600 GeV new quark  $Q$  can be searched for both at the Tevatron and the LHC. Standard searches are based on either (QCD) pair production or single production through electroweak interactions. Current bounds are in the  $m_Q \lesssim 385$  GeV region, depending on its preferred decay channel [13]. Single production through  $G$  in the  $s$ -channel together with a SM quark is therefore a novel mechanism. A detailed analysis of all possible decay channels and how competitive this single production can be with more standard searches is beyond the scope of this work and will be deferred to a forthcoming publication. (See [14] for a related discussion in the context of heavy gluons with fourth generation models.) It is important to emphasize, however, that some of these channels might produce non-standard signals that could be easy to miss if not explicitly searched for. As an example, if we take the case of a  $B$  with mostly charged current decays the final state would be exactly the same as that of  $t\bar{t}$ . The signal could then be missed because simple searches that do not use  $t$  reconstruction peak at  $\sim 500$  GeV, which is precisely where the peak in our model would show up, and more sophisticated analyses that include reconstruction could miss our signal because the two  $W$  come from the same leg. The case with lighter quarks, for example

$$q\bar{q} \rightarrow G \rightarrow U\bar{u} \rightarrow Wd\bar{u} \quad (7)$$

could be searched as  $W$  plus 2 jets.<sup>2</sup>

Another consequence of this scenario is the polarization of the top quarks produced at large values of  $m_{t\bar{t}}$ . In the model that we are considering the left-handed top quark does not couple to  $G$ . As a consequence, the forward (backward) excess (deficit) is defined basically by right-handed top quarks. The polarization can be measured in the subsequent decay  $t \rightarrow bl^+\nu_l$  from the distribution of the final lepton (see for example [16]).

Finally, the charge asymmetry in  $t\bar{t}$  production at large rapidities can be measured at the LHC in a wide range of  $m_{t\bar{t}}$  [3]. Our scenario predicts that the asymmetry changes sign at  $m_{t\bar{t}} = 800\text{--}900$  GeV. Notice that if the Tevatron could measure  $A^{t\bar{t}}$  above the

---

<sup>2</sup> If the coupling  $VQq$  with  $V = Z, W$  is large both the Tevatron and the LHC have good chances of discovering the new quark in single production [15].

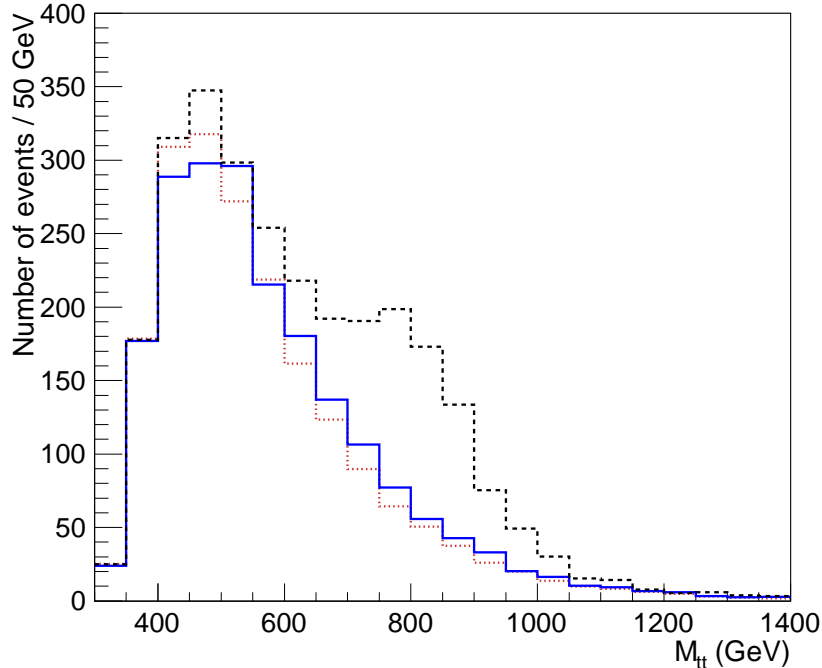


FIG. 2: Prediction for the  $m_{t\bar{t}}$  distribution at the LHC with a luminosity of  $1 \text{ fb}^{-1}$  for the SM (dotted) and for the model defined in Eq. (6) with (solid) and without (dashes) the new channel  $G \rightarrow U\bar{u}$ .

gluon mass it should also find a slight forward deficit. This very small and even negative charge asymmetry at large values of  $m_{t\bar{t}}$  can be an important test discriminating our model from other explanations of the Tevatron  $A^{t\bar{t}}$  (see [17] for a discussion in terms of effective operators).

## V. SUMMARY AND DISCUSSION

The large FB asymmetry observed at the Tevatron, if confirmed, is a sign of new physics at 450–800 GeV. This physics can compete with the color interaction, which suggests a strong coupling and a relatively light mass for the mediator. On the other hand, the absence of a peak in the  $t\bar{t}$  invariant mass distribution or of an excess of dijets at hadron colliders seem to imply that the new physics should be weaker and heavier, making difficult the definition of a working model. We have shown that all observations can be simultaneously satisfied if the mediator is a 800–900 GeV gluon with an additional decay mode into a SM quark  $q$

plus an extra  $Q$  quark of 400-600 GeV. The new channel does not change the physics below  $m_q + m_Q$ , preserving the FB asymmetry, but it suppresses the effects of the gluon at higher  $m_{t\bar{t}}$ . The signal from the  $Q$  quark is model dependent. In holographic models it could be one or several excitations of the light quarks or it may be a resonance of the right handed top-quark that decay mostly into  $Zt$  (or even  $Ht$  in models with a light Higgs). Some of the different possibilities for  $Q$  give rise to novel phenomenology that could be missed by standard LHC searches unless explicitly tailored analyses are used.

Another interesting feature of our setup is that the top-quark Tevatron excess in the forward direction is mostly composed of right-handed top quarks, which could be tested studying the angular distribution of the positron resulting from their decay. At the LHC, the charge asymmetry in  $t\bar{t}$  production at large rapidities should change sign at  $m_{t\bar{t}} \approx M_G$ .

We think that the best fit for the unexpected data on the FB asymmetry at the Tevatron is strongly coupled physics below 1 TeV. Our scenario is naturally realized in holographic Higgsless models. Thus, a clear consequence of such scenario at the LHC would be the absence of the light Higgs preferred by the SM or its SUSY extensions and no new physics up to energies around  $m_q + m_Q \approx 600$  GeV.

## Acknowledgments

We would like to thank G. Azuelos, F. Boudjema, G. Brooijmans, M. Felcini, U. Haisch, J.I. Illana, G. Moreau and S. Westhoff for useful discussions. This work has been partially supported by MICINN of Spain (FPA2006-05294, FPA2010-16802, FPA2010-17915, Consolider-Ingenio **Multidark** CSD2009-00064, and Ramón y Cajal Program) and by Junta de Andalucía (FQM 101, FQM 3048 and FQM 6552).

- 
- [1] V. M. Abazov *et al.* [ D0 Collaboration ], Phys. Rev. Lett. **100** (2008) 142002. [arXiv:0712.0851 [hep-ex]]; T. Aaltonen *et al.* [ CDF Collaboration ], Phys. Rev. Lett. **101** (2008) 202001. [arXiv:0806.2472 [hep-ex]]; T. Aaltonen *et al.* [ CDF Collaboration ], [arXiv:1101.0034 [hep-ex]].
  - [2] C. Degrande, J. -M. Gerard, C. Grojean, F. Maltoni, G. Servant, JHEP **1103**, 125 (2011). [arXiv:1010.6304 [hep-ph]]; C. Delaunay, O. Gedalia, Y. Hochberg, G. Perez, Y. Soreq,

- [arXiv:1103.2297 [hep-ph]]; J. A. Aguilar-Saavedra, M. Perez-Victoria, JHEP **1105** (2011) 034. [arXiv:1103.2765 [hep-ph]]; J. A. Aguilar-Saavedra, M. Perez-Victoria, [arXiv:1104.1385 [hep-ph]]; C. Degrande, J. -M. Gerard, C. Grojean, F. Maltoni, G. Servant, [arXiv:1104.1798 [hep-ph]].
- [3] CMS Collaboration, note CMS PAS TOP-10-010.
- [4] R. Barcelo, A. Carmona, M. Masip and J. Santiago, arXiv:1105.3333 [hep-ph].
- [5] C. Csaki, C. Grojean, H. Murayama, L. Pilo and J. Terning, Phys. Rev. D **69** (2004) 055006 [arXiv:hep-ph/0305237]; G. Cacciapaglia, C. Csaki, G. Marandella and J. Terning, Phys. Rev. D **75** (2007) 015003 [arXiv:hep-ph/0607146]; C. Csaki and D. Curtin, Phys. Rev. D **80** (2009) 015027 [arXiv:0904.2137 [hep-ph]].
- [6] P. H. Frampton, S. L. Glashow, Phys. Lett. **B190** (1987) 157; L. M. Sehgal, M. Wanning, Phys. Lett. **B200** (1988) 211; D. Choudhury, R. M. Godbole, R. K. Singh, K. Wagh, Phys. Lett. **B657** (2007) 69-76. [arXiv:0705.1499 [hep-ph]]; O. Antunano, J. H. Kuhn, G. Rodrigo, Phys. Rev. **D77** (2008) 014003. [arXiv:0709.1652 [hep-ph]]; A. Djouadi, G. Moreau, F. Richard, R. K. Singh, Phys. Rev. **D82** (2010) 071702. [arXiv:0906.0604 [hep-ph]]; P. Ferrario, G. Rodrigo, Phys. Rev. **D80** (2009) 051701. [arXiv:0906.5541 [hep-ph]]; P. H. Frampton, J. Shu, K. Wang, Phys. Lett. **B683**, 294-297 (2010). [arXiv:0911.2955 [hep-ph]]; Q. -H. Cao, D. McKeen, J. L. Rosner, G. Shaughnessy, C. E. M. Wagner, Phys. Rev. **D81** (2010) 114004. [arXiv:1003.3461 [hep-ph]]; D. Choudhury, R. M. Godbole, S. D. Rindani, P. Saha, [arXiv:1012.4750 [hep-ph]]; Y. Bai, J. L. Hewett, J. Kaplan, T. G. Rizzo, JHEP **1103** (2011) 003. [arXiv:1101.5203 [hep-ph]]; M. I. Gresham, I. -W. Kim, K. M. Zurek, [arXiv:1103.3501 [hep-ph]]; J. L. Hewett, J. Shelton, M. Spannowsky, T. M. P. Tait, M. Takeuchi, [arXiv:1103.4618 [hep-ph]]; U. Haisch and S. Westhoff, arXiv:1106.0529 [hep-ph].
- [7] A. Djouadi, G. Moreau and F. Richard, arXiv:1105.3158 [hep-ph].
- [8] D. Y. Bardin, A. Leike, T. Riemann and M. Sachwitz, Phys. Lett. B **206** (1988) 539.
- [9] J. Alwall *et al.*, JHEP **0709** (2007) 028 [arXiv:0706.2334 [hep-ph]].
- [10] T. Sjostrand, S. Mrenna and P. Z. Skands, JHEP **0605** (2006) 026 [arXiv:hep-ph/0603175].
- [11] PGS4 <http://www.physics.ucdavis.edu/~conway/research/software/pgs/pgs4-general.htm>
- [12] CMS Collaboration, note CMS PAS TOP-10-007; ATLAS Collaboration, note ATLAS-CONF-2011-087.

- [13] V. M. Abazov *et al.* [ D0 Collaboration ], [arXiv:1104.4522 [hep-ex]]; CDF Collaboration Note CDF/PUB/TOP/PUBLIC/10110; CDF Collaboration Note CDF/PHYS/EXO/PUBLIC/10243; ATLAS Collaboration Note ATLAS-CONF-2011-022.
- [14] G. Burdman, L. de Lima, R. D. Matheus, Phys. Rev. **D83** (2011) 035012. [arXiv:1011.6380 [hep-ph]].
- [15] A. Atre, M. Carena, T. Han, J. Santiago, Phys. Rev. **D79** (2009) 054018. [arXiv:0806.3966 [hep-ph]]; V. M. Abazov *et al.* [ D0 Collaboration ], Phys. Rev. Lett. **106** (2011) 081801. [arXiv:1010.1466 [hep-ex]]; A. Atre, G. Azuelos, M. Carena, T. Han, E. Ozcan, J. Santiago, G. Unel, [arXiv:1102.1987 [hep-ph]].
- [16] K. Agashe, A. Belyaev, T. Krupovnickas, G. Perez and J. Virzi, Phys. Rev. D **77** (2008) 015003 [arXiv:hep-ph/0612015].
- [17] J. A. Aguilar-Saavedra and M. Perez-Victoria, arXiv:1105.4606 [hep-ph].